

Data-Driven Energy Efficiency in Controlled Environment Agriculture

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ABSTRACT

This paper presents a resource benchmarking platform designed to support controlled environment agriculture (CEA) facilities. The platform benchmarks electricity, fuel, and water use to provide facility managers with three value propositions: 1) insight into their resource use, 2) support for the development of key performance indicators for energy use and productivity, and 3) prioritization of energy and water efficiency upgrades. We present data from more than 200 cannabis cultivation facilities along with case studies of growers that have used the data to guide significant facility efficiency upgrades. We also share preliminary data from a more diverse set of CEA facilities (i.e., non-cannabis).

Facility-level data collected through the platform offer a robust and expanding source of information on energy use in CEA; analyses of national energy consumption and efficiency potential in CEA based on the data are presented. Benchmarking of CEA facilities is a beneficial tool for program and policy design and implementation and for cultivator operations. We discuss examples of how the benchmarking platform is being integrated into programs and state-level policy.

Introduction

Agriculture is adapting as climate change affects field farming and food supply chains more often (Powell & Reinhard 2016). Extreme weather events cause billions of dollars in crop damage annually (Willenbockel 2012). Resilient harvests require efficient use of resources. The past year has proven that climate and market volatility continue to drive the CEA sector to become more productive. As more crops are grown in greenhouses and indoor farms, the value of benchmarking the performance of CEA facilities has never been greater. CEA facilities have diverse impacts on communities. Resource benchmarking tools like PowerScore give producers, governments, utilities, efficiency programs, and media the power to quantify the benefits of efficient approaches like LED horticultural lighting and automated controls.

Food production is responsible for 26% of the world's greenhouse gas (GHG) emissions (Ritchie and Roser 2019). Crop cultivation and supply chain processes require energy and generate associated emissions. Globally, 78% of GHG emissions come from the production and consumption of energy (Government of Canada 2020). CEA facilities use a variety of sources of energy depending on the facility type and the location, including electricity and fuels like natural gas and propane (RII and ACEEE 2021).

PowerScore is a free tool from the nonprofit Resource Innovation Institute (RII) that applies benchmarking, a proven strategy for ongoing efficiency improvements (EPA 2021), to the specific needs of CEA facilities. It customizes benchmarking solutions for controlled environment agriculture facilities. Quantifying the resource use of indoor farms and greenhouses has not yet been done at the industry level. Data on facility level energy and water consumption

provide valuable insight to producers, utilities, government, and consumers about the social and environmental impacts of innovative agricultural approaches and identify opportunities to improve production efficiency while reducing overall environmental impact.

CEA Benchmarking Overview

Protected agriculture, “crops grown under glass or other protection,” provides the broadest definition of CEA cultivation approaches (USDA 2019). Greenhouses, indoor farms, and seasonal hoop houses cultivating food crops (e.g., leafy greens, tomatoes, peppers, mushrooms, berries), floriculture crops (e.g., young plants, ornamentals, cut flowers, bedding plants), and medicinal crops (e.g., cannabis) are all CEA facilities.

As the CEA industry expands and consumes more resources to drive production, it is imperative to benchmark more facilities to verify the environmental impacts and benefits of CEA approaches. CEA facilities use less land to grow more food with less waste. Tomato greenhouses can achieve 15 times higher production per unit of crop canopy and lower yield losses than outdoor tomato farms, with 90% of the harvest making it to market (Padmanabhan, Cheema, and Paliyath, 2016). Indoor CEA facilities can be more than 4,000 times more productive on a revenue basis than outdoor farms (Agrilyst 2016).

Benchmarking is one of the best leverage points to help CEA producers overcome barriers to the widespread adoption of energy efficiency practices. It helps producers validate the performance of their operations, increase their understanding of technologies and their benefits, and demonstrate success via analysis of key performance indicators (KPIs) and case studies. Widespread benchmarking of a diverse range of production approaches and facility types in many locations can demonstrate efficiency benefits based on size and method of cultivation and help producers gain a better understanding of and value for the benefits of efficiency.

Specialized tools for benchmarking unique agricultural facilities like greenhouses and indoor farms measure the range of energy and water performance across the CEA industry. Resource-efficient agricultural operations are more resilient in the face of climate change and economic volatility, but data to validate the efficiency of CEA facilities are not yet transparently shared among key market actors. Benchmarks for energy efficiency, water efficiency, and productivity for greenhouses and indoor farms are not available to the market. Data necessary to quantify the impacts of CEA approaches are collected by producers, but until 2017 when PowerScore began to benchmark cannabis cultivation facilities nationally, an independent and rigorously vetted platform for benchmarking KPIs did not exist (RII 2017).

PowerScore

PowerScore is RII’s specialized resource benchmarking platform for CEA crop production facilities. As PowerScore has served CEA cultivation facilities for the past five years, the worldwide CEA industry has seen rapid growth in several crop categories. In 2018, a compound annual growth rate (CAGR) of 3.4% was estimated for the United States CEA market between 2018 and 2023 (Mordor Intelligence 2021). The 2017 US nursery, greenhouse, and floriculture market of nearly 50,000 operations was valued at \$20 billion (USDA 2017). The nearly 3,000 operations growing fruits, vegetables, and herbs in the United States cultivate produce valued at \$1.4 billion (USDA 2019). The US vertical farming market has been valued at \$740 million and is forecasted to grow at 10.5% CAGR to reach a \$3 billion valuation by 2024 (Mordor Intelligence 2020). The US legal cannabis cultivation market has also grown rapidly,

increasing from 2.6 million to 9.8 million pounds of production between 2017 and 2021; the industry is projected to increase by 102% between 2020 and 2025 (RII 2021).

PowerScore generates up to 15 KPIs for resource efficiency and productivity of energy and water, and emissions like solid waste and GHG impacts of energy use. The platform gives facility managers insight into their resource use, supports the development of KPIs for energy use and productivity, and prioritizes energy, water, and emissions efficiency upgrades (RII 2022).

The PowerScore platform includes intake websites and surveys, facility Performance Snapshots, crop-specific Ranked Data Sets, user profiles, dashboards, and comparative analysis reports. Its free service enables producers to enter self-reported data through the online PowerScore platform to get a Performance Snapshot sharing KPIs and measuring year-over-year changes in facility performance. Figure 1 below shows an example Performance Snapshot with facility-level and crop-level KPIs for energy efficiency and productivity showing year-over-year 14.4% better facility performance.

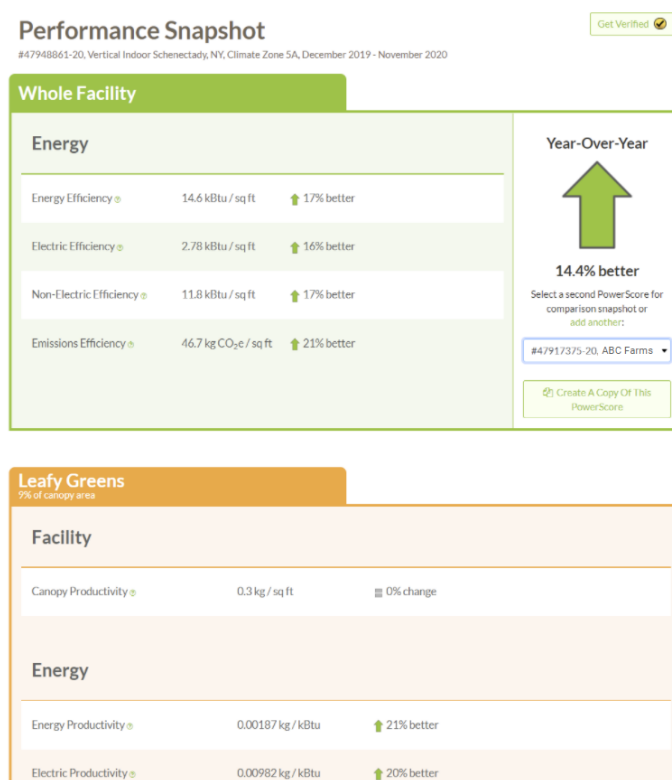


Figure 1. PowerScore Performance Snapshot for a vertical indoor farm growing leafy greens. Figure demonstrates KPIs and uses modeled facility performance, not actual data.
Source: RII 2022.

Crop-Specific Ranked Data Sets

The PowerScore platform provides useful insights to all key market actors interested in a resource-efficient CEA industry. Producers, regulators, efficiency programs, and supply chain

actors use PowerScore Pro to access crop-specific Ranked Data Sets to benchmark performance by cultivation type and create regional baselines. RII shares trends in aggregate performance of CEA industry segments to describe the environmental impacts of cultivation to media organizations (Fertig and Bade 2021).

PowerScore represents the largest analysis of aggregate resource usage data on CEA environments. For CEA markets where there is a statistically significant crop-specific Ranked Data Set, Performance Snapshots provide an unverified informative Facility Ranking. Figure 2 below shows an example Performance Snapshot with facility-level and crop-level KPIs for energy, water, and emissions efficiency and canopy productivity KPIs showing a Facility Ranking of 45th percentile and a year-over-year 24.4% improvement in facility performance.

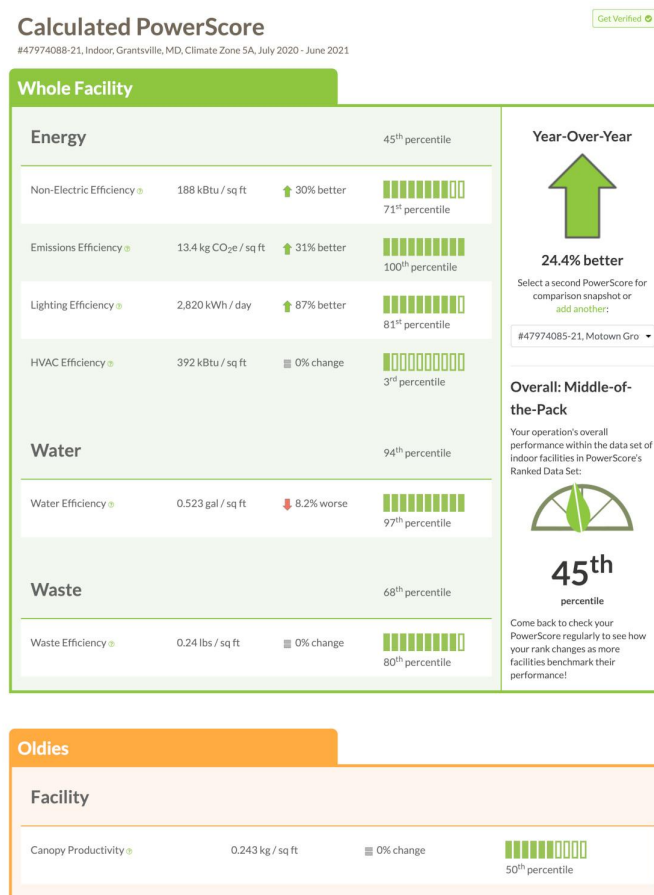


Figure 2. PowerScore Performance Snapshot for an indoor farm growing cannabis. Figure demonstrates facility rankings and uses modeled facility performance, not actual data. *Source:* RII 2022.

CEA Facilities Producing Cannabis

PowerScore has been used to benchmark hundreds of cannabis production facilities across the United States in the past six years. In 2022, more than 200 PowerScore records for cannabis cultivation operations have valid data used to calculate a facility energy KPI. Table 1 presents the energy and water KPIs of indoor cultivation facilities in PowerScore's Ranked Data

Set for cannabis (RII 2022a). There were 125 indoor facilities in the Cannabis Ranked Dataset as of March 2022.

Table 1. Ranges of performance for indoor facilities in PowerScore Cannabis Ranked Dataset

Key Performance Indicator (KPI)	Units	Minimum	Average	Maximum
Indoor cannabis facility energy efficiency	kBtu per canopy square foot	374	2,090	5,560
Indoor cannabis facility electric energy efficiency	kBtu per canopy square foot	67	1,050	5,460
Indoor cannabis facility non-electric energy efficiency	kBtu per canopy square foot	0	934	3,130
Indoor cannabis facility water efficiency	gallon per canopy square foot	0.5	136	520

Source: RII 2022.

Table 2 presents the electricity and water efficiency KPIs of greenhouse cultivation facilities in the PowerScore Ranked Dataset for cannabis. There were 57 greenhouse facilities in the Cannabis Ranked Dataset as of March 2022.

Table 2. Ranges of performance for greenhouses in PowerScore Cannabis Ranked Dataset

Key Performance Indicator (KPI)	Units	Minimum	Average	Maximum
Greenhouse cannabis facility electric energy efficiency	kBtu per canopy square foot	3	262	1,500
Greenhouse cannabis facility water efficiency	gallon per canopy square foot	4	73	304

Source: RII 2022.

Data from cannabis facilities suggest that greenhouses can achieve electric energy efficiency KPIs much better than those of indoor facilities. Average greenhouse cannabis facility electric energy efficiency is 89% better than average indoor cannabis facility electric energy efficiency, likely driven by a lower need for sole-source lighting. Average and maximum greenhouse cannabis facility water efficiency are 46% and 41% better than average indoor cannabis facility water efficiency, respectively.

CEA Facilities Producing Other Crops

In 2020, RII and ACEEE were awarded a Natural Resources Conservation Service (NRCS) Conservation Innovation Grant from the United States Department of Agriculture (USDA) for a project titled “Data-driven market transformation for controlled environment agriculture” (RII 2020a). As part of the project, the PowerScore tool was expanded to serve non-

cannabis cultivation operations (RII 2022b). Other CEA benchmarking tools have been supported by NRCS; COMET-Farm, developed by Colorado State University, supports GHG accounting for farms and ranches. The USDA Agricultural Research Service developed and maintains Virtual Grower to simulate energy savings of different greenhouse designs and is expanding to model vertical farms and the crop impacts of emerging technologies. Energy service professionals also use independent tools to perform energy audits, analyze energy efficiency and GHG reduction potential of farms, and predict energy savings.

Since June 2021, RII has worked with a cohort of non-cannabis CEA producers to benchmark their greenhouse facilities and vertical indoor farms (2021). While few crops have the same energy intensity as cannabis, there are significant efficiency opportunities in existing CEA operations and in new facility design and construction. For all CEA facilities, efficient use of electricity is a key opportunity for producers and efficiency programs.

Preliminary data from CEA facilities suggest that greenhouses growing food and floriculture crops can achieve electric energy efficiency KPIs much better than those of cannabis facilities. Table 3 describes the average electric and water efficiency of indoor cultivation facilities in the emerging PowerScore Dataset for non-cannabis crops. Average indoor CEA facility electric energy efficiency is 18% of average indoor cannabis facility electric energy efficiency, likely driven by a lower demand for sole-source lighting from food and floriculture crops.

Table 3. Average performance for indoor facilities in PowerScore CEA dataset

Key Performance Indicator (KPI)	Units	Average
Indoor CEA facility electric energy efficiency	kBtu per canopy square foot	192
Indoor CEA facility water efficiency	gallon per canopy square foot	94

Source: RII 2022.

Preliminary data from CEA facilities growing a more diverse set of crops suggest that non-cannabis greenhouses can achieve electric energy efficiency KPIs much better than those of cannabis greenhouses. Table 4 describes the electric efficiency of greenhouse cultivation facilities in the emerging PowerScore Dataset for non-cannabis crops. Average greenhouse CEA facility electric energy efficiency is 23% of average greenhouse cannabis facility electric energy efficiency, likely driven by a lower demand for supplemental lighting from food and floriculture crops.

Table 4. Average performance for greenhouse facilities in PowerScore CEA dataset

Key Performance Indicator (KPI)	Units	Average
Greenhouse CEA facility electric energy efficiency	kBtu per canopy square foot	60

Source: RII 2022.

Benchmarks for indoor and greenhouse facility non-electric energy efficiency range more widely and can depend on HVAC system type and climate zone. Natural gas use in non-cannabis

CEA operations in colder climates may account for 48–67% of total annual energy use, while natural gas use in warmer regions may account for as little as 4% of total annual energy use (RII 2022c).

Emerging Trends in CEA Facility Performance

Growers using PowerScore use KPI trends and year-over-year performance to guide significant facility efficiency upgrades. Cannabis, food, and floriculture producers alike benefit from understanding facility resource efficiency, canopy productivity, and associated impacts on operational expenses and revenue. Benchmarking activities can reduce resource use and GHG emissions from CEA operations by giving producers the KPIs necessary to continuously improve and align with the high-performance baselines of the CEA market.

CEA facilities located in regions with high energy costs will have greatest financial benefit from resource benchmarking of facility energy efficiency. As costs of energy continue to rise, the return on investment for efficient equipment like LED horticultural lighting and greenhouse curtains will become shorter. In addition, investment in energy upgrades like more efficient HVAC helps reduce the impact of future rising utility costs.

RII analyzes average performance of cannabis operations to validate best practices and applications of emerging technology. Average performance of 84 indoor cannabis cultivation operations demonstrated that those using LED lighting for flowering growth stages achieved 34% better average electric facility efficiency. Facilities using LED lighting systems averaged 606 kBtu per canopy square foot compared to an average of 882 kBtu per canopy square foot for non-LED systems (MacIver 2020). These values align with the savings reported by efficiency programs targeted to lighting upgrades in cannabis facilities (ComEd 2021).

Many non-cannabis greenhouses and indoor farms can use automated environmental controls, LED horticultural lighting, and greenhouse curtain technology to support production and research activities while also providing cost-effective payback periods. An academic greenhouse growing food and floriculture crops uses PowerScore to quantify the benefits of installing LED light fixtures and replacing greenhouse curtains. The greenhouse facility is planning to replace thermal curtains in 2022 and has used PowerScore to establish baselines using data from electricity bills and controls system trend data to quantify steam usage. Future PowerScore Performance Snapshots can verify actual energy savings of the curtain replacement.

The greenhouse facility is limited by electrical service and has been unable to operate supplemental lighting in all houses, requiring some houses to sit dormant in 2020 and previous years. In 2021, the greenhouse converted 20% of canopy area using supplemental lighting to LED with support from its local energy efficiency program. This project increased facility space in use by 6%, allowing for more research and production activities, which increased the value of canopy area by 17%. By installing LED instead of high-intensity discharge (HID) light fixtures in the expanded space, the university also avoided a 9% increase in annual electricity usage.

RII estimated the electrical energy and demand savings from replacing remaining greenhouse HID light fixtures with LED would reduce electricity use by 24% and reduce annual electric bills by more than \$9,000 (including peak demand savings of \$4,000 per year). Comprehensive LED fixture replacements could pay back within five years with support from energy efficiency incentives. Since the facility benchmarked with PowerScore and shared estimated energy demand savings with its local energy efficiency utility, the incentive offer for the comprehensive replacement increased to \$280 per fixture from \$150 per fixture offered in 2021, further shortening payback periods.

CEA Energy Impacts

Facility level data collected through PowerScore offers a robust and expanding source of information on energy use in CEA. Operators can quantify the benefits of sustainable strategies like efficient building systems and high-performance controls and automation methodologies and vet environmental solutions by calculating KPIs for energy, water, and emissions impacts of CEA facilities (RII 2020b).

National energy consumption and efficiency potential in CEA can be extrapolated from emerging PowerScore baselines for cannabis and non-cannabis greenhouses and indoor farms. By implementing efficiency upgrades identified and benchmarked with PowerScore, 10,000 non-cannabis greenhouses and vertical farms could save 26 billion kBtu of energy, 2 billion kg CO₂eq of GHG, and 5 billion gallons of water.¹ If cannabis facilities implement efficiency upgrades in the same manner as food and floriculture facilities, energy savings could be almost eight times larger.

CEA Benchmarking for Efficiency Programs and Government Policies

Benchmarking of CEA facilities benefits energy efficiency program implementers designing programs and governments crafting policies to regulate cultivation businesses. In the absence of larger historical datasets on CEA industry energy use and trends, benchmarking provides critical insight into the resource efficiency of CEA facilities. This energy performance data is vital for utility planning, facility siting and permitting, and development of effective energy efficiency programs. The information is also crucial for effective policymaking like the design of energy codes and standards, jurisdictional regulations, and requirements for energy use transparency. Cultivators who benchmark before mandates get a competitive advantage by understanding KPIs and beginning their continuous improvement journey earlier.

Efficiency Program Design

Research with CEA producers has found that growers would benefit from technical assistance and incentives to support identification and installation of efficiency upgrades for their facilities (ComEd 2021). Receiving this technical assistance and engagement from trusted, unbiased sources is especially important for cannabis, food, and floriculture growers. Upfront cost is an acute issue for CEA producers, with impacts on the energy efficiency of greenhouses and indoor farms. Lack of knowledge about and trust in efficient technologies and their performance are also significant barriers (RII and ACEEE 2021).

Benchmarking with an independent platform like PowerScore can complement efficiency program technical assistance and establish a mechanism for producers to conduct ongoing tracking of their facility performance and participate in strategic energy management programs. Benchmarking CEA greenhouses and indoor farms is also an identified market transformation strategy to establish baselines and KPIs for the industry and generate efficiency success stories (RII and ACEEE 2021a).

¹ This assumes a 4:1 mix of greenhouses to vertical farms. Savings are based on facility energy use estimates reported by ACEEE in 2018 and an assumed 20% savings for implementation of efficiency upgrades like LED horticultural lighting and greenhouse curtains.

PowerScore has helped shape best practices for efficiency programs serving cannabis and non-cannabis cultivation operations by informing members of RII's Utility Working Group of the Technical Advisory Council since 2019 (2022d). CEA KPI insights support the guidance efficiency programs share with the market (RII 2022e). Benchmarking facilities before and after efficiency projects is recommended for effective CEA customer engagement and strategic energy management programs (RII 2022f).

Energy Codes and Standards

Cultivators of cannabis are already affected by regulations addressing lighting and HVAC system design and operation in some states, including Massachusetts and Illinois. Policy changes affecting CEA facilities are also happening crop agnostically through energy codes. The International Code Council (ICC) has accepted proposals to change the Lighting for Plant Growth and Maintenance section to include minimum photosynthetic photon efficacy (PPE) requirements for horticultural lighting (DOE 2020). In 2021, the California Energy Commission and California Building Standards Commission adopted and approved the 2022 California Title 24, Part 6 Building Energy Efficiency Standards (i.e., building code), including the state's first requirements for indoor and greenhouse cultivation facilities. The new code provisions address horticultural lighting, dehumidification equipment, and greenhouse coverings that will go into effect on January 1, 2023 (Energy Solutions and Cultivate Energy Optimization 2020).

Industry standards for CEA are also emerging to support regulatory activities, supply chain quality, and better outcomes for producers. The DesignLights Consortium's Qualified Product Library for LED horticultural lighting uses standards from the American Society of Agricultural and Biological Engineers to validate performance of this emerging technology being promoted by energy efficiency programs. The national standard for energy-efficient buildings maintained by ASHRAE, Standard 90.1, includes an addendum that proposed horticultural lighting efficacy and controls requirements similar to those adopted in Title 24, Part 6. The second public comment period for BSR/ASHRAE/IES Addendum closed in April 2022 (ASHRAE 2022). Depending on the timing of regional code cycle updates, as jurisdictions adopt the addendum addressing horticultural lighting equipment and controls, CEA growers may have local building codes that reference 90.1 affecting retrofits and new construction as soon as 2022, or in the next few years (Schimelpfenig 2021).

Best practices guidance to support design and construction professionals with HVAC and lighting for CEA facilities have emerged alongside standards. Examples include Heating, Ventilation, and Air Conditioning (HVAC) for Indoor Plant Environments without Sunlight (ANSI/ASABE/ASHRAE) Engineering Practice 653, the Illuminating Engineering Society's Recommended Practice: Horticultural Lighting RP-45-21, and RII's Best Practices Guides for cannabis and CEA facility optimization.

Energy Use Transparency

Of all CEA operations, cannabis cultivation facilities are the most affected by benchmarking requirements at the state and local levels.

Massachusetts was the first jurisdiction in the world to feature cultivation guidelines and regulations to improve resource efficiency. Along with lighting system requirements, the regulations require submission of facility energy-use data at the time of license renewal or new license application. PowerScore is specified as a compliance mechanism for the state's data

submission requirements (CCC 2020). Licensees can choose one of two online surveys: PowerScore Comply, which meets regulatory requirements, or PowerScore Comply and Benchmark, which gathers additional information to calculate competitive KPIs not submitted to regulators (RII 2022g). The state uses PowerScore to collect annual energy consumption, onsite renewable energy generation, peak electric demand, and annual production to calculate environmental impacts of the cannabis market using KPIs like grams per kWh (RII 2022h). Vermont's Regulation of Cannabis Establishments for licensed cannabis businesses applies energy regulations to both indoor and greenhouse cultivation facilities and requires energy usage reporting of energy efficiency benchmarks (CCB 2022).

In 2018, Goleta, California, added a requirement to the city's Cannabis Land Use Ordinance requiring growers to use PowerScore and to participate in energy efficiency programs (City of Goleta 2021). Since 2020, the County of Ventura, California, has required commercial cannabis cultivators to submit Energy Conservation Plans, including an analysis of energy use and a plan for achieving a 25% reduction in energy use with energy efficiency, on-site renewable energy generation, and/or green power purchases (County of Ventura 2020). Baseline energy usage for licensed indoor and greenhouse cannabis facilities is calculated using a PowerScore baseline (County of Ventura 2020a). In 2022, Mendocino County, California, is implementing PowerScore reporting requirements for cannabis permit applications and renewals.

Conclusion

Published data on the energy use and energy performance of CEA facilities is limited. Rapid growth in greenhouse production and the emerging vertical farm sector are driving interest in the energy demand of these facilities and opportunities for energy efficiency. Benchmarks for validating the energy performance of CEA facilities provide a mechanism to transparently share energy data among key industry actors and meet a crucial need for effective market transformation. RII's free PowerScore tool applies benchmarking—a proven strategy for ongoing efficiency improvements—to the specific needs of indoor agriculture facilities. Benchmarking with PowerScore arms producers with specialized KPIs to measure and verify the environmental impacts and benefits of their approaches and quantify the benefits of efficiency projects in greenhouses and indoor farms.

Aggregate ranges of performance for energy, water, and emissions KPIs are necessary for policymakers, program administrators, and key market actors to quantify the environmental impacts of the CEA industry and describe their scale with data. As the Cannabis Ranked Data Set has grown, PowerScore data illustrate the opportunities for energy efficiency programs incentivizing electric and natural gas savings. As the CEA Ranked Data Set grows, comparisons by crop type, facility construction, and location all provide more transparency for the market to establish baselines and celebrate successful operations achieving high-performance KPIs.

As data from CEA benchmarking improve our understanding of energy use in these facilities, we establish the basis for future recognition of excellence in energy and water performance. Future integration of the PowerScore platform into more policies and programs can transform the CEA industry with benchmarking that informs regulatory activities at the federal, state, and local levels.

A data-driven market transformation approach for the CEA market supports informed strategies and coordinated producer support systems like energy codes, industry standards, and efficiency programs. Coordination and support strategies for producers and other key market

actors have the potential to advance this component of a resilient agricultural future for humanity.

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